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A global environmental assessment of electricity generation technologies with low greenhouse gas emissions

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Abstract

Limiting climate change by stabilizing the global temperature requires the near complete phase-out of conventional fossil fuel power generation and its replacement through technologies with low greenhouse gas emissions, such as renewable energy, nuclear power, and fossil fuel power plants with CO_2 capture and storage. We investigate the environmental and resource co-benefits and adverse trade-offs for a wide range of candidate electricity generation technologies using an integrated life cycle approach. Most renewable energy technologies provide substantial benefits in terms of emission reductions. Additional material demand for manufacturing energy conversion devices ranges between 0.1 and 3 times annual global production in 2010.

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Keywords:

1. Introduction

Anthropogenic climate change is phenomenon through which the increased concentration of gases which absorb infrared radiation leads to a temperature increase (greenhouse effect). This change can only be stopped by stabilizing the concentration of such greenhouse gases (GHG) in the atmosphere. Today, electricity production, with a share of 30%, is the single largest source of anthropogenic GHG emissions (IPCC WGI).

Nomenclature

CCS	CO_2 capture and storage
CSP	Concentrating solar power
IEA	International Energy Agency
LCA	Life Cycle Assessment
NGCC	Natural gas combined cycle power
PV	Photovoltaic power

1.1. Goal and scope

Renewable energy production, nuclear power and CO_2 capture and storage are technologies that are available to substantially reduce GHG emissions from power production through replacing conventional fossil power plants. Some studies point to substantial co-benefits in terms of reducing conventional air pollution, while others point to additional material demand, up-front energy investment in the manufacturing of energy technologies, and impacts associated with land use and habitat disturbance. Policy makers have hence requested the International Resource Panel under UNEP to study co-benefits and adverse side-effects of different low-GHG power generation technologies. The study is comprised of a comprehensive literature survey of a wide range of identified environmental and resource issues investigated in the scientific literature and a prospective life-cycle assessment modelling that evaluates the impact of a wide-spread adoption of low-GHG technologies as foreseen by GHG mitigation scenarios. In this paper, we summarize the study results for life-cycle assessment (LCA). Coal and gas

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fired power with and without CCS, hydropower, wind power, photovoltaic power, and concentrating solar power (CSP) were selected because they all play an important role in future energy scenarios and their impacts have received much less attention than nuclear power and bioenergy. The functional unit is the generation of 1 kWh of electricity in one of the world regions. The full report is expected to be published in 2014 (1).

2. Methods

2.1. Life cycle inventory modelling

In order to conduct a scenario-based, prospective assessment of the wide-spread introduction of energy technologies, Gibon et al. (2) developed the integrated hybrid life cycle inventory model θεmis (*Technology Hybridized Environmental-economic Model with Integrated Scenarios*). θεmis combines a description of the world economy through a 9 region multiregional input-output model (3) with the technology detail offered by the EcoInvent 2.2 database (4), including recent updates. θεmis has the capability to integrate the output of the foreground system, such as electricity generation, back into the economy, so that the electricity used for the manufacturing of technology in question comes from the described system.

The foreground life-cycle inventory data comprising both process level and economic data was collected by different teams of experts. Inventories have been or are being published separately. For the technologies addressed, following sources have been used:

- Wind, based on studies in Europe (5, 6)
- Concentrating Solar Power, based on US cases (7, 8)
- Photovoltaics, based on production in China and US (9, 10)
- Fossil fuel power plants with and without CCS, based on a US assessment (11, 12)
- Hydropower, based on case studies from Chile

For the up-scaling and prospective analysis, we modelled the levels of technology implementation in 2030 and 2050 according to the Blue Map and Baseline scenarios of IEA (13).

2.2. Life cycle impact assessment

The Recipe (H) method was employed to assess life cycle impacts at the midpoint and endpoint levels (14). The report includes intermediate results for land, non-renewable energy, and selected base materials (iron, copper, aluminium, cement). Midpoint indicators address the contribution to specific environmental mechanisms, such as climate change through changes in the radiative balance of the planet, eutrophication through the mobilization of plant nutrients, or the contribution to particulate matter formation causing respiratory cardiovascular health problems. Endpoint indicators estimate the impact on specific protection subjects such as humans or non-human species (ecosystems).

2.3. Scenario analysis

The application of different electricity generation technologies was up-scaled to the level of application in each region seen expected in 2010, 2030, and 2050. The life cycle inventory for future electricity technologies was adapted to reflect some changes in technology expected. Foreground technologies change, mostly in terms of efficiency and capacity factors as reflected in the IEA scenario, and selected technologies such as PV were also adapted to reflect expected technological change (thinner solar cells). The background technologies were changed (i) to reflect the change in energy mix reflecting the IEA scenarios and (ii) the performance improvement in selected material production reflecting life cycle assessment scenarios defined by the NEEDS project (15). The scenario analysis hence provides an insight into the future development of total emissions from the selected electricity production technologies, reflecting both the effect of changes in the technologies that generate electricity, the effect of increase electricity generation, and the effect of changes in the life cycle impacts of the technologies with time.

3. Results

3.1. Life cycle inventory

The life cycle inventory contains information on the intermediate inputs to the production of the technology, the primary resource requirements, and resulting pollution, for each individual technologies modelled in each of the nine regions for the years 2010, 2030 and 2050. Here we present the demand for bulk materials, nonrenewable energy and land for the implementation of each technology in the United States in 2010 (Fig 1). Fig. 1a shows that renewable energy technologies cause a higher demand for bulk materials than fossil fuels. Concentrating solar power (CSP) and wind have the highest demand for iron and steel (Fe) and cement, mostly connected to the structures required for power generation. Photovoltaic technologies have the highest requirements copper (as conductors) and aluminium (as mounting structures). Hydropower, as shown here, is comparable to other renewable technologies.

Fossil technologies have the largest requirements of non-renewable energy, mostly as fossil fuel employed directly in the power plant. In terms of bulk material flows, a coal fired power plant requires on the order of 300 g fuel per kWh, which is much larger than the requirements of structural or functional materials of renewable power.

All power plants are to some degree dependent on local circumstances, such as the availability and temperature of cooling water for thermal power plants, the distribution of wind speeds or the strength of direct sunlight for wind and CSP, respectively. However, no technology is as variable as hydropower. The life cycle requirements of different hydropower plants, however, differ widely, and the investigated power plants do not constitute a representative sample of power plants.

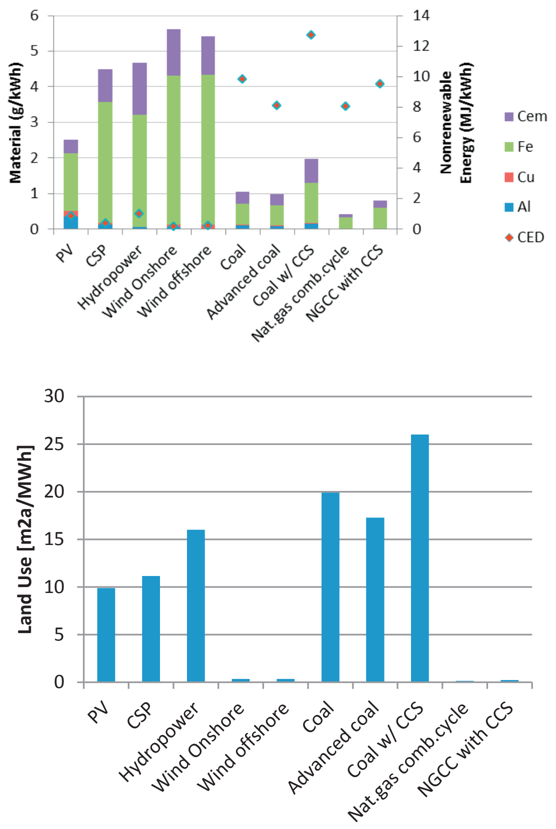

Fig. 1. (a) Requirements of bulk materials (Al ..aluminium; Cem .. cement; Cu .. copper; Fe .. iron&steel) and nonrenewable energy throughout the life cycle of different energy technologies; (b) Land occupation per unit electricity produced in square-meter-years per MWh.

Renewable power is well recognized to have high land use requirements due to a low energy density (Fig. 1b). Compared to solar power or storage hydropower, the land occupation of wind energy, measured as the footprint of the power plant and the infrastructure (roads, transformer stations etc.) required, however, is low. Fig. 1b indicates that coal power has the highest he occupation over the life cycle. This high land occupation is related to mining. For surface mines, it is the land occupied by the mine pit itself that constitutes the highest land requirements. The underground mines in EcoInvent rely on hardwood as structural support for the mine shafts, and the land required to grow this wood is even larger than that of surface mines. In the United States, the majority of the coal comes from underground mines; in other regions can be somewhat lower than that of renewable sources. Please note that for wind power, the land required for entire wind parks is on the order of 200 m^2a/kWh. Commercially, this land can be used for agriculture or as pasture, but it cannot be used for residential developments; in terms of ecological impact, many species are not impacted by the wind power plants apart from the direct land use; however, birds and bats collide with rotating wings and are hence impacted over a larger area.

3.2. Life cycle impact assessment

Fig.2 shows the life cycle impacts of the different power technologies as implemented in the United States in 2010. The figure indicates that renewable energy technologies generally have lower impacts on climate change (greenhouse gas emissions measured by the 100-year global warming potential). Particulate matter exposure constitutes the most significant environmental health according to the comparative risk project of the World Health Organization; renewable technologies also cause lower particulate matter than fossil technologies. A similar picture arises for freshwater ecotoxicity. For freshwater eutrophication, caused primarily by phosphate emissions, natural gas fired power also has low impacts. Renewables also outperform fossil fuels and coal power in particular for other environmental indicators in the Recipe set of indicators (1), and this is true across all regions. The comparative LCA hence indicates that renewable energy technologies have lower pollution impacts than coal fired power and most gas fired technologies.

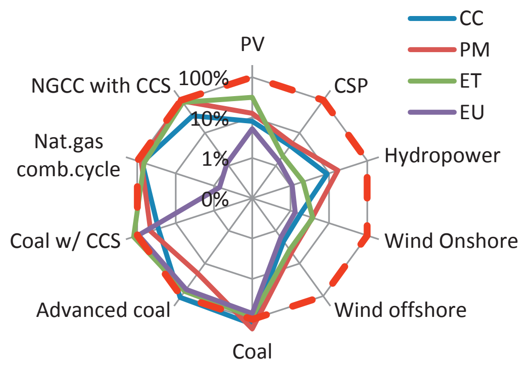

Fig. 2: Comparison of life cycle impacts of the investigated power plants, normalized to the current impact of the US electricity mix. Impact categories shown are climate change (CC), particulate matter exposure (PM), freshwater ecotoxicity (ET) and freshwater eutrophication (EU).

3.3. Scenario analysis

The scenario analysis broadly reflects the results of the life cycle assessments: in the Blue Map scenario, which achieves a reduction of GHG emissions by 50%, environmental impacts are reduced, but material demand increases (Fig. 3). Pollution indicators either go down or at least remain stable (eutrophication) for the period to 2050, while material demand associated with electricity production increases up to fourfold. Land occupation and non-renewable energy requirements remain constant. We compared the use of the four bulk materials to current production levels: For iron, one month's production is sufficient to produce the power generation equipment utilized in 2050; for copper, three times the annual production is required. Copper is increasingly mined at lower ore grades and has limited deposits at concentrations interesting to mine; in contrast to iron and aluminium which are abundant. Functionally important, minor metals have not been investigated in the LCA, but our review indicates that they may limit the application of particular technologies, such as InTe-thin film PV cells or permanent-magnet based direct drive wind turbines, but that they do not provide a fundamental constraint to utilizing any of the renewable resources.

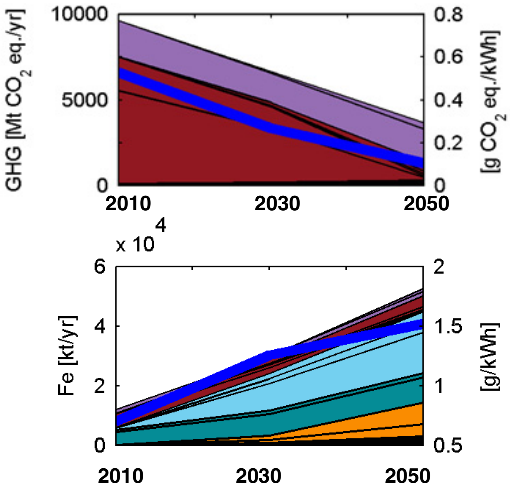

Fig. 3: (a) Scenario for greenhouse gas emissions and (b) the demand of iron and steel associated with the generation of electricity using the investigated energy sources (PV, CSP, wind, hydro, coal, gas) following the IEA Blue Map scenario. The figure shows the total demands (left axis) and the intensities of the mix (right axis, blue line).

4. Discussion

Our investigation shows clear benefits of moving from fossil to renewable energy technologies in terms of a reduction of a wide range of pollution impacts. These benefits come at the price of increase material demand. This increased demand is considered in the LCA and does not out-weigh the pollution gain from reduced fossil fuel combustion and mining.

How certain can we be of these conclusions? There are some elements that we have not explicitly modelled in our LCA:

- There are some impacts not traced by the indicators in question, such as visual impacts or impacts on wild-life through habitat change (e.g. hydropower) and collisions (wind power).
- Intermittent renewable energy production, primarily from PV and wind power requires a change in the operation of the grid. At high levels of penetration, either larger grid areas are required to balance the generation, the operation of backup power, or flexible demand. At even higher levels of penetration, energy storage may be required. The impacts of such adjustments has not yet been well studies and depends on a number of characteristics of the local grid, so that generic answers are not possible. However, investigations in Europe indicate that the GHG impacts can be comparable to those of the primary generation equipment, e.g. the wind turbines and PV plants. While costly, such adjustments still have a small impact.

It should be further noted the impacts of power generation can be limited through the selection of the appropriate technologies and projects and appropriate management steps.

Our study indicates that renewable energy technologies and CCS offer ways to reduce GHG emissions and that of those technologies, renewable power has the lower environmental impacts.

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